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ARPA Network Information Center
Stanford Research Institute
Menlo Park, California

NIC #20396
Packet Radio Temporary Note #82

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23 November 1973

THE DAMN (-FINE) CONCEPT

I INTRODUCTION

The acronym DAMN (-FINE)* has been chosen to represent a Dynamically Allocated Multiple-channel Network (For Improved Network Efficiency). It might equally have been chosen as the DYNATAC-ALOHA Multiple-channel Network, since many of the concepts are drawn from these two multiuser networks. The DYNATAC network is a mobile-radio voice network proposed recently by Motorola on FCC Docket #18262. It consists of an array of fixed, independent transmitting and receiving sites interconnected by telephone cable in a network with a centralized control, and a set of hand-held voice terminals which can be synthesizer-tuned under remote digital control to any of many narrow-band frequency channels. The DYNATAC centralized control automatically allocates channels to a terminal-transmitter site-receiver site triplet. These channels are fixed for the duration of a communications transaction although the transmitter/receiver may change. Thus the channel is not available to any other user in the same area, although it may be reused over and over on a noninterfering basis at other locations. The DAMN system concept draws upon the DYNATAC concept to provide many geographically reusable narrow-band channels; however, it discards the disadvantage of a hard-wired, centrally controlled network, using circuit switched channels. To avoid the inefficiency of circuit switching for digital data, the DAMN system draws upon the University of Hawaii ALOHA system as extended by the packet radio project. In the DAMN system each channel is time-shared among several mobile users and a repeater. The

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* Hereafter referred to as the DAMN system. The reader may introduce the parenthetical (FINE) if he is so inclined.

hardwired network of transmitter-receivers is replaced by a network of portable (but fixed) repeaters which are interconnected by rf links, chosen from the same channel set. The repeater channels are also time-shared a-la ALOHA (with a carrier-sense modification). The centralized control is replaced by an adaptive channel search and selection algorithm in each repeater and terminal which effectively distributes the control, but provides for very efficient dynamic allocation to match changing traffic and interference patterns. Because the DAMN system searches passively for channels, and because it is a frequency channelized system it can be readily overlaid on existing systems with minimal mutual mutual interference. It requires no active cooperation in allocation of channels. The DAMN system uses only the resources it needs, and carefully selects the resources from those which are not used by existing systems.

The purpose of this note is to suggest a design concept for the DAMN system which embodies much of the knowledge and research reported in the Packet Radio Notes, and which seems to meet all of the system design criteria so far voiced by the Packet Radio Working Group.

Briefly, the design criteria considered are:

1. The system should provide error-free communication of digital data between a mobile terminal and a station with minimum network delay.
2. The system should use the spectrum efficiently.
3. The system should be compatible with existing users.

4. The system should not stress technology unnecessarily.

5. The network should be readily expandable as users are added.

The degree to which the DARN system meets each of these criteria will be discussed in a subsequent section after the system concept is described in some detail.

The suggested system includes many speculative, or undefined concepts in the area of network organization, routing, flow control, hardware design, etc. This has been necessary in order to quickly bring the concept before the Packet Radio Working Group. It is hoped that other members of the group will criticize, modify, add to and otherwise improve the idea if it has merit.

II DESCRIPTION OF THE DAMN SYSTEM

A. System Concept

Figure 1 represents the suggested DAMN system concept. It is a network with a station, a hierarchy of repeaters, and terminals which are repeater-associated. The station has a multichannel capability which is dynamically allocated to best fit the traffic patterns. The channels are narrow-band (100 kHz) Minimum-Shift-Keyed channels. The dynamic allocation is not centrally controlled, and requires no complicated control algorithms. Each terminal and repeater automatically select a channel which is least busy. Only when there are not enough repeaters in a given area to handle the area traffic will overload occur. Furthermore, if a high-duty cycle user enters the net he will cause other lower duty cycle users to avoid or leave the channel he selects, so that he will eventually obtain a channel well matched to his requirements.

As suggested in Figure 1, each channel is centered on a frequency which can be used in several noninterfering areas simultaneously. The DAMN system uses many relatively narrow-band frequency channels and the DAMN station has the capability of operating on several of these simultaneously. The repeaters can operate on any two frequencies and the terminals on any one. The frequencies may be selected at random anywhere within the allocated band. Figure 2 shows a hypothetical situation in which a heavily used mobile radio band has been selected in which to set up the DAMN system. Because of the nature of the distributed dynamic control, the DAMN system will automatically select

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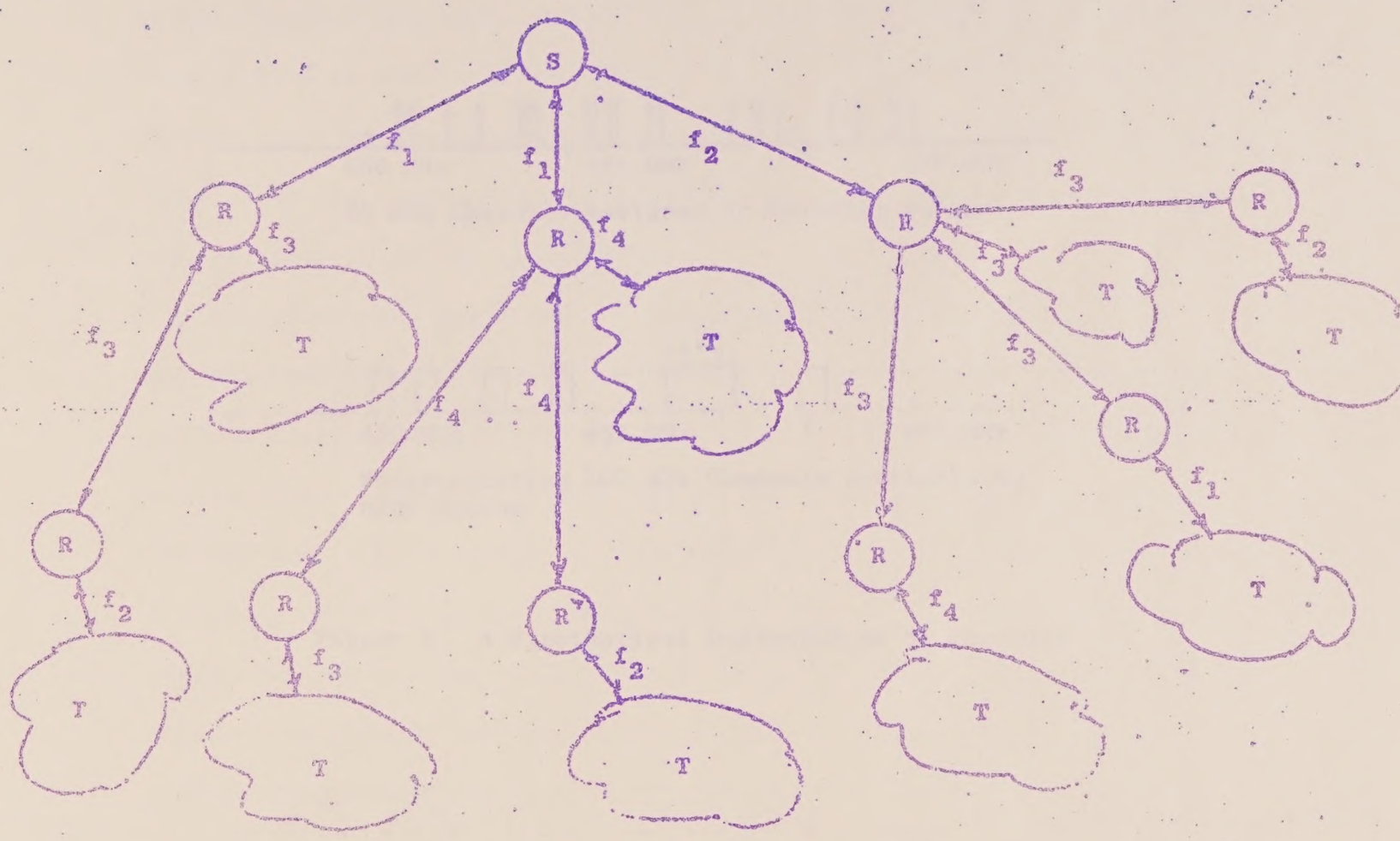
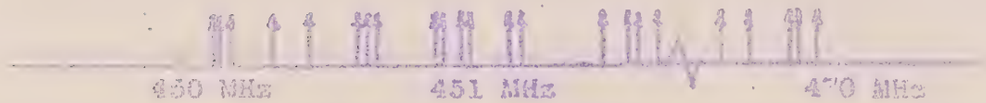


S = Station
R = Repeater
T = Terminal

f_1 ⟷ = channel at frequency f_1

Figure 1 Typical DAMN System

20 MHz Allocated Band : 100 kHz Channels



25 kHz Channels Assigned to Existing Users

Noninterfering 100 kHz Channels Available to DARN System

Figure 2 A Hypothetical Distribution of Channels

noninterfering frequencies. If an interfering user comes up on a DAMN frequency, the interferer will cause a reallocation so that the new frequencies will again be noninterfering.

Because the interference pattern will change from area to area and because the DAMN system can adapt to different interference patterns and reuse frequency channels in different geographical areas, it is possible that a DAMN system could operate effectively in an area where the frequency band would be considered completely allocated, or in a frequency band where the number of narrow-band signals would make operation of a spread-spectrum system impractical.

To understand the nature of the suggested distributed control suppose that a user at a mobile terminal wishes to initiate a communications-transaction with the station; that is, he wants to send a message and receive a response. Let us follow the signaling sequence through the network. The terminal is designed to periodically scan all possible frequency channels and to determine which channels are being used by nearby repeaters. The terminal also estimates activity in each nearby channel and selects that one which is least loaded. In this way the load is dynamically allocated to achieve an even distribution over the channels, but no centralized channel allocation control is needed. A possible channel-search algorithm is illustrated in Figure 3 to show the simplicity of this control method. Thus, when the user inputs his message, the terminal has already decided which channel to use. The message is transmitted and response received on this channel using a Carrier-sense access

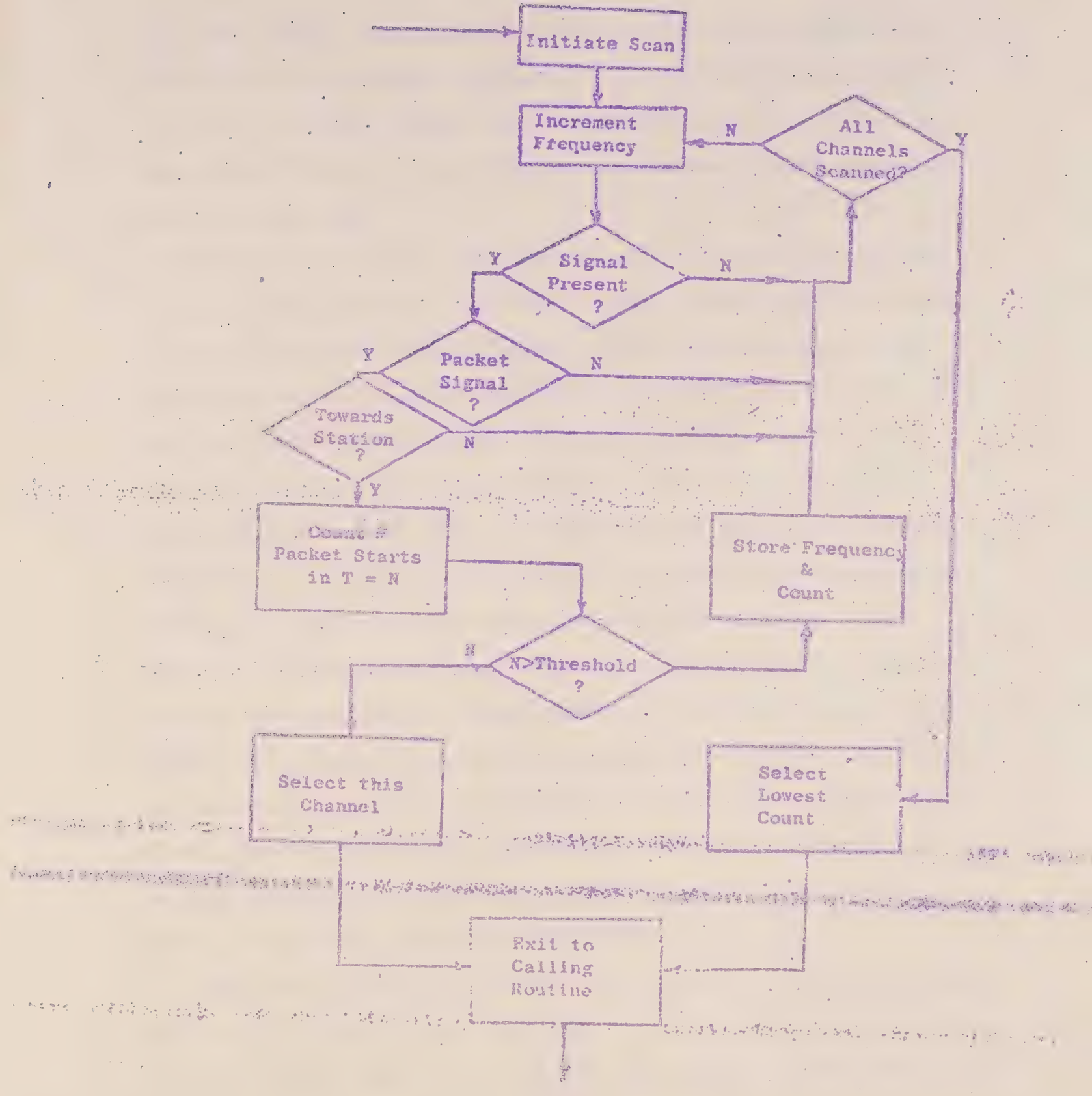


Figure 3 A Terminal Channel-Selection Algorithm Flow Chart

mode. The terminal will continue to use its first-chosen channel until the end-to-end delay becomes excessive. If this occurs it will initiate a scan to find another channel which may provide less delay either because the new repeater is less busy, or because the new route through the network is less busy.

Meanwhile the repeater which will receive the message has selected two channels for operation. One (the outbound channel) will carry traffic to and from repeaters farther from the station and to and from local-area terminals (this is the channel which our terminal will select); and the second (the inbound channel) will carry traffic to and from the repeaters next on the route to the station. The inbound channel is selected using the same criteria as used by the terminal. The repeater initially scans all channels to find the least-busy inbound repeater (or station) that can be reliably heard, and chooses this channel. The repeater will continue to use this channel until retransmissions become excessive at which time the repeater initiates a search for a new inbound channel. Retransmission may become excessive either because the inbound repeater channel is loaded, or because the inbound route is loaded. In either case, the repeater will automatically initiate a channel search, and the load will be reallocated, if a better channel is available, without the necessity of a centralized control.

The outbound channel is selected by the repeater initially by scanning the channels to find an empty one. This channel is monitored for a short period of time to assure that it is not being used by a nonnetwork member

(such as a radar or air-to-ground voice communication system) with a low duty-cycle. Then the repeater begins to periodically broadcast "beacon" packets to tell terminals and other repeaters that this channel is available to be used for inbound traffic. As the inbound user load builds up a corresponding outbound load will also build up so that the dummy beacon packets need not be sent.

When the repeater receives the message sent by our user terminal, it will acknowledge receipt on the outbound channel and repeat the message on the inbound channel using a Carrier Sense mode.

The station must establish a link with each nearby repeater. A number of strategies are possible. For example the station might scan all channels, find an empty one (just as the repeater finds an outbound channel), and transmit periodic "beacon" packets until traffic builds up to the point where beacon packets are no longer needed, and finally, until the traffic approaches channel capacity. At this point a second channel is established by sending beacon packets on another empty channel. This requires that the station be able to operate on several channels simultaneously; however, any multichannel system must have the same capability. Initially a single repeater can be used as the rf part of a station, providing dual-channel capability. As the network grows so that more channels are needed, additional repeaters can be integrated into the station.

B. DAMN Hardware

1. The DAMN Universal Module (DUM)

Figure 4 is a functional block diagram of a DAMN universal module (DUM) for the system. This module is straightforward and can be

constructed largely from off-the-shelf hardware. With the exception of the micro processor, the Motorola "Dynatac" hand-held terminal contains all of the DUM components plus a power supply and audio I/O components in a package with the following characteristics:

Size	1-7/8" x 3-1/2" x 9"
Weight	45 ounces.

This package was designed to operate in the 900 MHz mobile radio band, providing 200-400 frequency channels with 1 watt output power. The package contains audio components, and digital control logic which uses at least as much volume, weight, and power as the DUM microprocessor and control logic; thus it is apparent that an extremely small, lightweight DUM can be readily developed.

2. Application of the DUM to Network Components

Figures 5, 6, and 7 illustrate how the DUM is used to build up a station, a repeater, or a terminal. The major change in a DUM when operating as part of these three system components is in software in the microprocessor. This software, in fact, is relatively simple, since it need implement only the three search strategies required of station, repeater, and terminal; however, the software may be difficult to implement in minimum memory and minimum speed configuration probably required for off-the-shelf microprocessors. Nevertheless, the software development is a one-time effort and the cost is amortizable over many units.

Packaging of the DUM will undoubtedly be different for repeater, station, and terminal due to the differing mobility and environmental

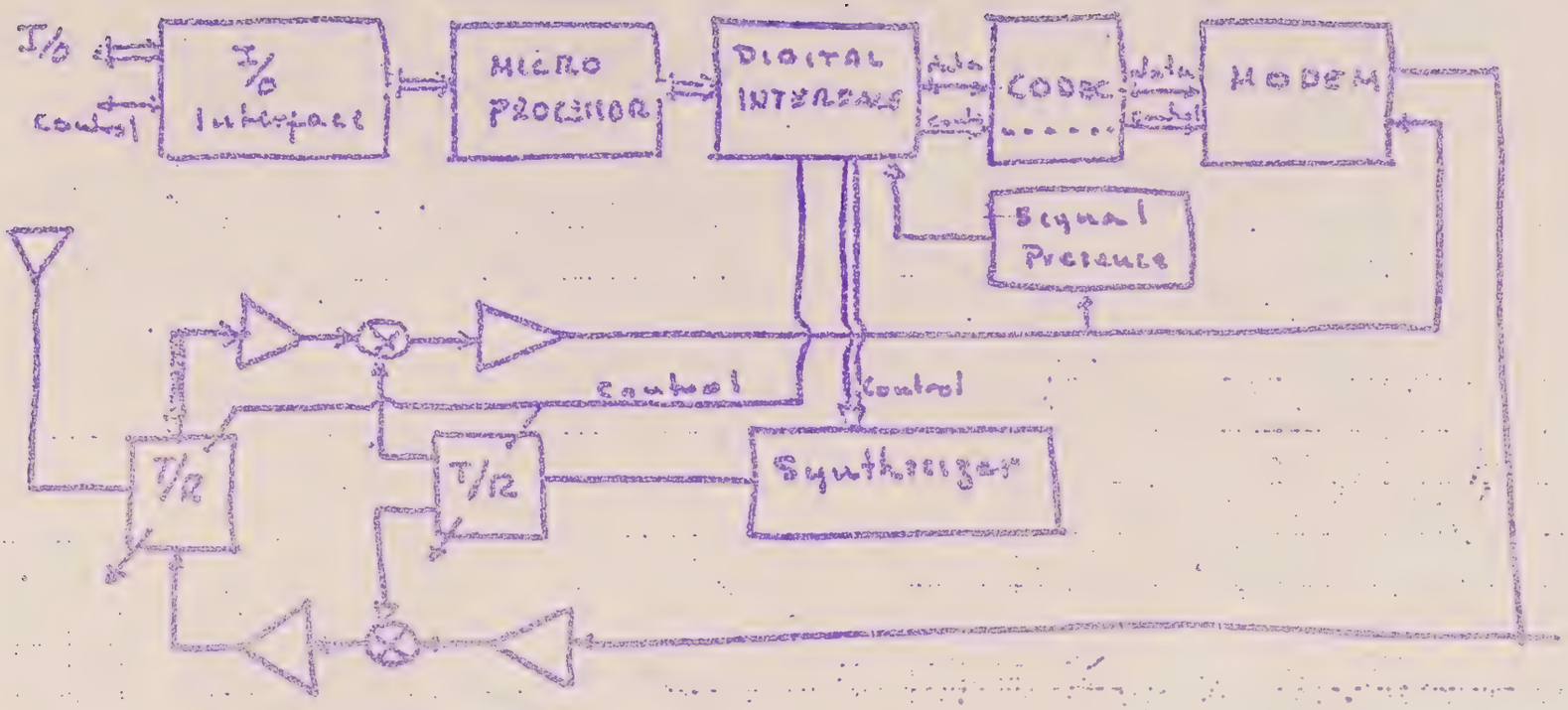


Fig 4 - DAMN UNIVERSAL MODULE

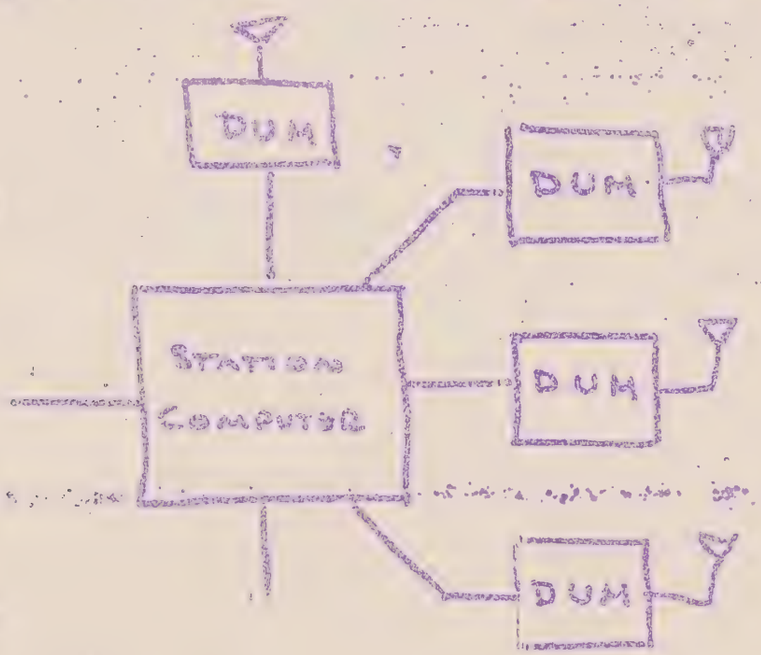


Fig 5 - STATION CONFIGURATION

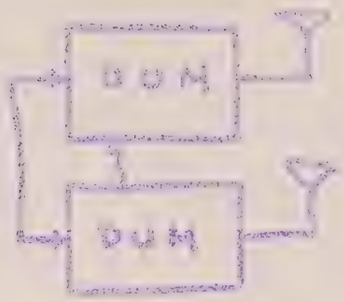


FIG. 6 REPEATER CONFIGURATION

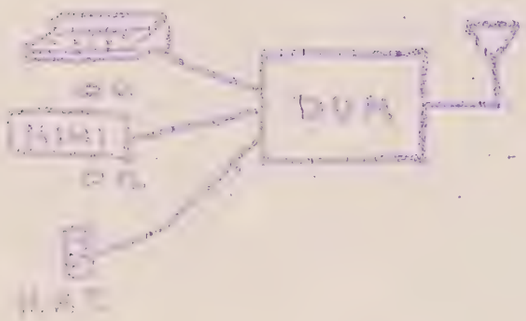


FIG 7 TERMINAL CONFIGURATION

factors. Also, it will probably be desirable to provide either an add-on module to increase the radiated rf energy at the station and repeaters, or to provide the DUM in two power-sizes; one, perhaps 10W transmitted power for stations, repeaters and portable terminals where power-drain are not critical; a second, perhaps 1W, for hand-held and ultrasmall portable terminals where size and weight consideration are critical.

3. The DUM Functions

a. I/O Interface

Returning to Figure 4--we see that the DUM I/O interface must be able to connect a wide variety of I/O devices to the microprocessor. The interface should be universal in the sense that it can operate with a large computer (station), minicomputer, keyboard-printer, or another DUM interface. It must be able to accept and offer data in parallel 8 or 16 bit bytes, and provide the necessary control signals to handle I/O [illegible].

b. Microprocessor

The microprocessor must perform many functions:

1. I/O
2. Formatting messages into packets
3. Addressing
4. Routing and flow control
5. Channel search and selection algorithms
6. Carrier-sense channel access control
7. Acknowledgment generation and checking.

Not every application of the DUM requires all functions, and the functions vary from one application to another, e.g. channel search algorithms are different for repeater and terminal. Thus the microprocessor must be programmable. Perhaps it is possible to develop a station ROM, repeater ROM, and terminal ROM which could be plug-interchangeable to provide the software flexibility.

c. Digital Interface

The digital interface must provide an interface between the parallel data operations of the microprocessor and the serial data operations of the codec and modem. In addition it must perform certain fixed-logic functions such as address checking which would require excess data handling in the microprocessor. It provides control signals to the synthesizer and the T/R switches, and interfaces the signal-present signal into the microprocessor. In certain application, such as at the station it may be desirable to be able to transfer data directly through the digital interface to the I/O port, so the digital interface may provide a DMA channel which bypasses the microprocessor. This last feature is not necessary and need not be implemented if it requires excessively-complex or power consuming circuitry.

d. The Codec

The codec encodes and decodes the digital data. If error detection proves adequate, the codec may be a simple convolutional codor and parity checker. If impulsive noise proves excessive, some more complicated error-correction codec may be required.

e. The Modem

The modem maps the encoded digital packet into a sequence of analogue waveforms suitable for rf transmission. The modem also maps received analogue waveforms into a sequence of binary digits for decoding. The modem must also develop the necessary synchronized clock signals to control all sequential operations of the codec and digital interface. The modem should probably use an MSK (minimum-shift-keyed) type of modulation in a phase-differential mode since this will provide for maximum reliability and use minimum bandwidth for a given radiated power, bit rate, and background noise level.

f. The rf Components

The rf portion of the DUM consists of the antenna, T/R switch, transmitter, receiver, synthesizer and signal-presence detector. The antenna should be plug-changeable so that omni and directional antennas can be interchanged if desired. This may be particularly useful at the station.

The T/R switches control the state of the DUM and must operate as rapidly as possible to provide for efficient channel utilization. It may be necessary to synchronize two T/R switches in the repeater DUM's if separate antennas, carefully designed IF filters, and channel selection algorithms cannot provide adequate channel isolation.

The receiver rf amplifier must cover the entire band of channels so that tuning is not required. Probably a double-conversion if will be necessary to provide the necessary selectivity and channel

isolation. One of the conversions must be synthesizer-controlled so that all channels are digitally selectable. Channel bandwidth is nominally 100 kHz to pass the nominal 100 kB MSK signal. Since contiguous channels can be avoided, it is probable that some overlap of channels is acceptable.

The transmitter must up convert the modulated signal to the proper channel and amplify it to provide the required output power. The power amplifier should be power-controlled so that the microprocessor acting through the digital interface can adjust the ERP to the optimum level for network operation.

The synthesizer is the only difficult component in the rf section. It must be capable of generating a stable sine wave at any one of the possible frequencies of operation. Furthermore, during the search mode it must be rapidly switched from one frequency to another while the signal-detector is sampled to determine whether the channel is occupied. Such a synthesizer is clearly possible as demonstrated by the prototype DYNATAC terminal.

The signal-presence detector should be a simple energy-detector with a digitally-controlled threshold setting so that the microprocessor can define the energy level at which a signal is considered to be present. The analog level of the energy detector should be available to the microprocessor so that the relative signal quality on each occupied channel can be evaluated when the terminal is searching for a repeater channel.

III PRELIMINARY PARAMETERS AND ANALYSIS

A. Parameters

In order to provide a concrete basis for comparison with alternative system concepts a preliminary set of parameters has been chosen. No attempt has been made to optimize these except that those principles so far established in the Packet Radio Notes have been applied when possible.

1. Frequency of operation

   1300-1400 MHz

2. Bandwidth occupied

   20 MHz entire possible band

   100 kHz individual channel

3. Modulation

   MSK

4. Bit rate

   100 kbps

5. Terminal and Repeater power

   10 watts

6. Channel Access mode

   Carrier Sense

B. Comparison with Design Criteria

It is too early for a detailed analysis, but we can make some preliminary estimates of performance for comparison with other systems.

1. Delay and Throughput Efficiency

The achievable delay and throughput will depend very much on the network details; however, we can determine the delay-throughput for a single repeater-terminal area. Since Carrier Sense will be used the results of Kleinrock/Tobagi PRN # 75 will apply. Because an MSK signaling scheme is chosen the throughput represents efficiency in bits/Hz.

Since the frequencies are geographically reusable it is likely that in a large network the efficiency for transmissions far from the station will be greater than one bit per Hz, even for small delays. Efficiency of the overall network will be determined by the efficiency of the bottleneck at the station. Even though the station has multiple channels, none can be used more efficiently than the carrier-sense access mode will allow. The overall network efficiency will probably approach carrier sense very closely; however, delay will depend on routing and flow control procedures and cannot be analyzed at this time.

It is clear that if multiple stations are used in a given area, the overall efficiency of bandwidth use can exceed one bit per Hz for very reasonable delays. This is not possible with many alternative systems which do not allow geographical reuse of channels.

2. Compatibility

The DANN system is readily compatible with other types of users in the 1300-1400 MHz band. If sufficient time is given to each repeater

to assure that the channel selected for operation is not in use, the system will not interfere with active users. The only type of interference experienced by other users will be on channels which have very low duty cycle. These channels will be abandoned by repeaters after a short period of contention. If the channel-selection mechanism is carefully designed the period of interference should not exceed the duration of a few packets, since the repeater can quickly tell when interference is not packet-network generated.

3. Practicality

The DAMN system concept requires much more study, research, and analysis, but the components can be constructed using off-the-shelf technology. The only development risk involved is one of software; however, careful packaging development effort is clearly needed.

4. Flexibility

The DAMN system seems to be extremely flexible. Furthermore, it makes efficient use of bandwidth in all size networks. It is readily adaptable to a single station with a few terminals, to a single station, multirepeater network, or to a multistation multirepeater network. A large network can readily be implemented one repeater at a time, and no interference need be experienced. As traffic concentrations occur due to changing user patterns the network is easily modified by adding or removing repeaters. Furthermore, so long as repeaters are not isolated by propagation, the network will not fail catastrophically due to the failure of a few repeaters.

5. Operation in Multipath

Since the system operates with 100 kHz, 100 kBps channels, and since excess multipath delay rarely exceeds 5 us (1/2 bit duration) the proposed system would be immune to the intersymbol-interference effects of multipath.

Because of the multiple frequency operation, the effects of fading on a terminal repeater propagation path can be largely avoided.

The DAMN system is almost multipath-proof.

IV SOME ALTERNATIVES

Although the suggested concept seems to be acceptable, there are several alternative designs that deserve examination.

A. Variable Bit Rate

It is possible that a more efficient network would result if each DUM had software-selectable bit rate, so that a single repeater could handle the traffic in a sparcely populated area. Decreasing the bit rate would extend the range of the repeater-terminal link. As pointed out in PRN #28, there exists an optimum bit rate for a given user density and fixed transmitter power. This relation could be used to select bit rate.

B. Spread Spectrum Modulation

The variable bit-rate might also be used to provide some security if it was implemented using a fixed-chip-rate of 100 k chips/sec spread-spectrum system. As the bit-rate is decreased, the spread-factor is increased and either energy per bit is increased, or the energy density in watts per Hz is decreased. The former provides greater range, or some anti-jam protection, the latter provides lower detectability. This mode of operation would use chip-synchronized code-generators to avoid the vulnerability of a fixed-code system.

C. Multiple Bit Rate

It would also be possible to provide the DUM with two or more bit-rates. One could be used for terminal-repeater traffic and the other for repeater-repeater traffic. This might reduce network delay significantly but would probably not affect efficiency.

D. Directional Antennas

The concept can be implemented using only omnidirectional antennas. It is possible that lower power could be used on the repeater-repeater channels if one DUM in each repeater (used to repeat inbound and outbound traffic) were provided with two directional antennas. This does not appear to be desirable since it would require some setup on initial installation, and would make the net more vulnerable to failure of a single repeater.

E. Other Access Modes

It might be possible to improve overall network efficiency by using some form of reservation channel in the link between station and first-echelon repeaters. Since these links will effectively limit the channel efficiency, and will carry the most traffic it is likely that a reservation scheme will improve the network significantly.

V COST

The DAMN system is based on the use of a DUM with each terminal, two DUM's with each repeater, and many DUM's with each station. Terminals will require some additional I/O components, and the station will require additional computing capability and interface to other communication networks. Since all packet-radio networks require the terminal and station elements, the cost of the DAMN concept can be compared to the cost of other concepts by examining the cost of the DUM, and comparing it to the cost of the RF part of other networks.

We cannot readily determine the cost for other networks, but we have a convenient cost measure for the DUM, since it is similar to the DYNATAC hand-held terminal. The exact cost of this terminal is not available in Motorola's literature; however, they are proposing a network in New York, for example, to include 189,000 users. They believe that such a market exists at the hand-held terminal price. This suggests that the hand-held terminal price must be no greater than current mobile-telephone instrument price which is on the order of $500 - $2,000.

VI IMPLEMENTATION

Initially an elementary network could be implemented as represented in Figure 8 . It should consist of one DUM programmed to act as the outbound half of a repeater, and several DUM's programmed to act as terminals. This network can serve to work out hardware bugs in the DUM, evaluate and develop inbound and outbound channel search algorithms, and examine the impact of a real RF environment on the concept. Many of the basic concepts of dynamic allocation cannot be evaluated with such a small network, but RF compatibility and individual channel performance can be tested.

To evaluate some of the more complex concepts involving multirepeater operation, a multirepeater net would be required. The first step would be to implement two repeaters and a station as shown in Figure 9 . This would require at least six DUM's. In addition six or more DUM's programmed as terminals are needed.

The hardware for these elementary networks should be made as small and lightweight as off-the-shelf technology will allow. A DUM can certainly be built in a small attache case with little packaging effort. With some packaging effort a DUM should be smaller than the DYNATAC hand-held terminal. Perhaps this packaging effort should await the results of tests with a multiterminal network.

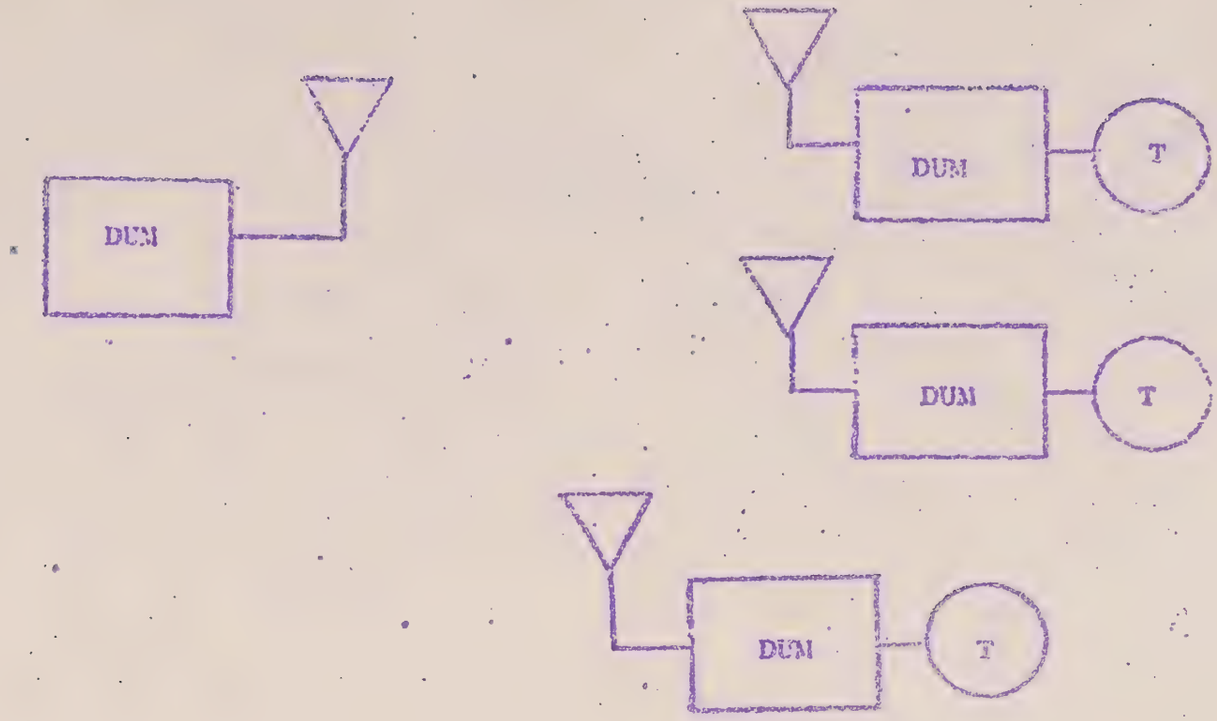


Figure 8 Elementary Net

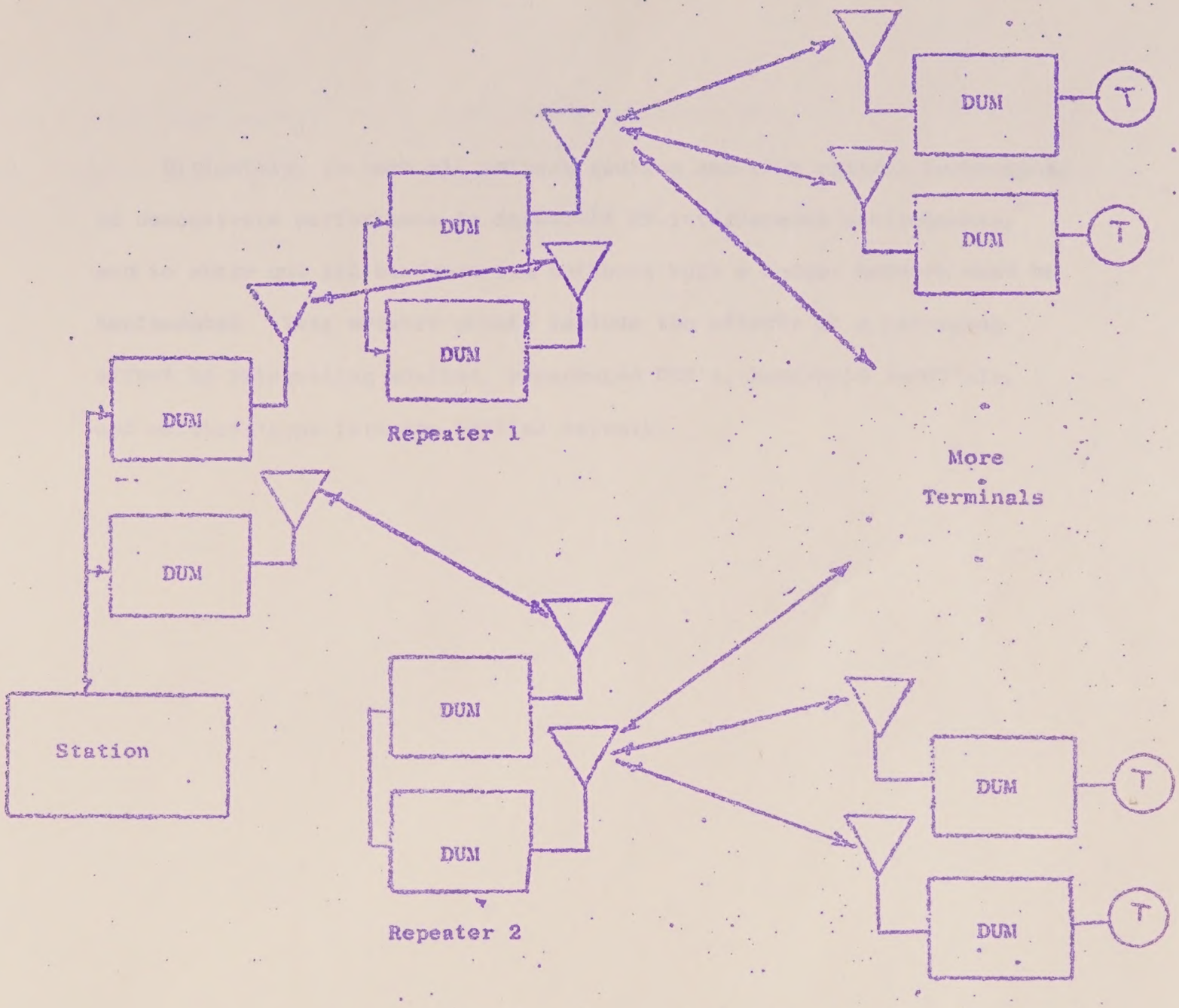
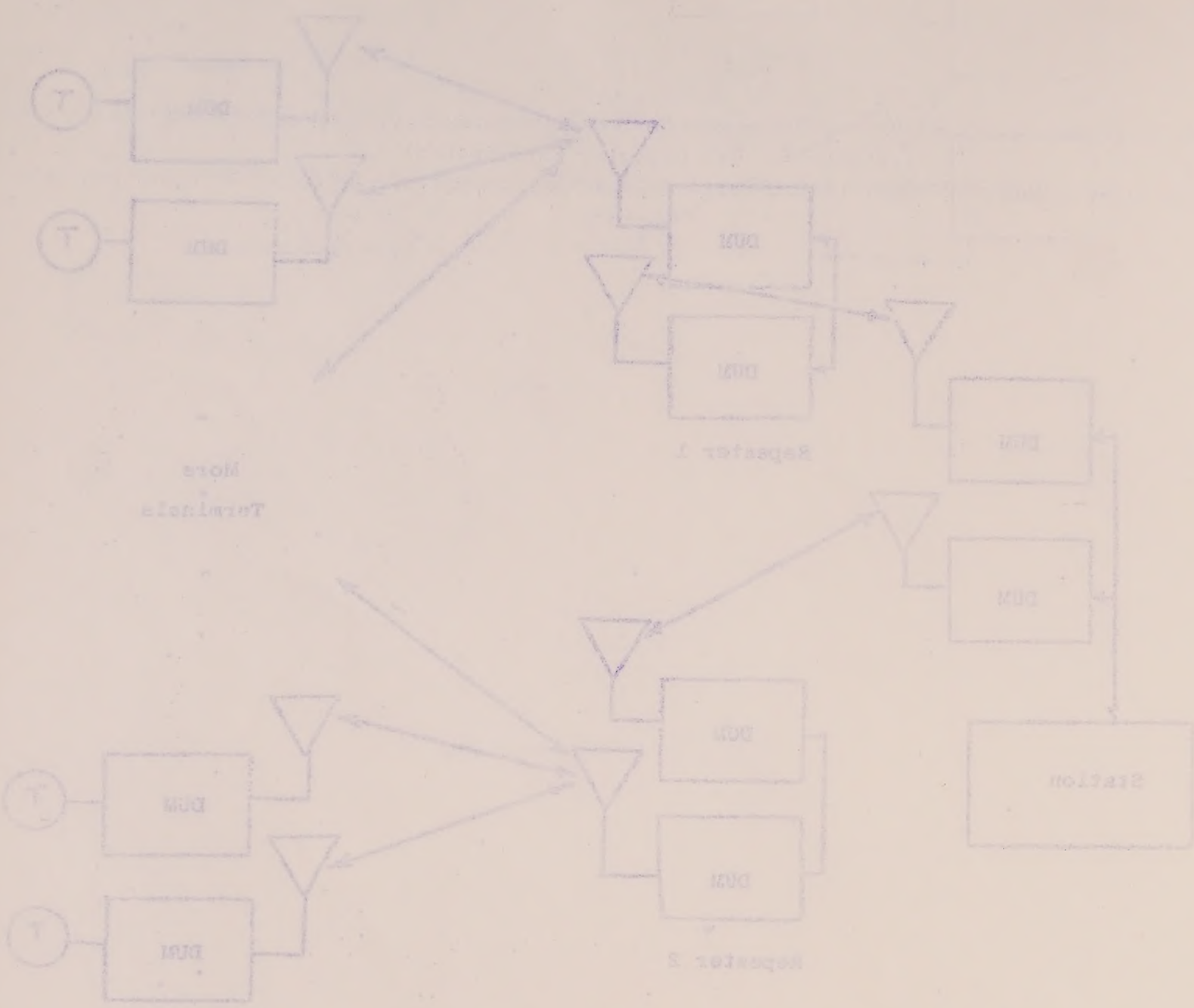


Figure 9 Two Repeater Experimental Net



Ultimately, to test all network routing and flow control techniques, to demonstrate performance in difficult RF-interference environments, and to shake out all hardware and software bugs a larger network must be implemented. This network should include the effects of a packaging effort by integrating smaller, repackaged DUM's, hand-held terminals, and multistations into the initial network.